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Laboratory Validation of a Resource Quality-Based Conceptual Framework for Organic Matter Management

B. Vanlauwe,* C. Gachengo, K. Shepherd, E. Barrios, G. Cadisch, and C. A. Palm

ABSTRACT

Organic resources (ORs) are essential inputs in tropical farming systems and their decomposition dynamics are related to their quality. A Decision Support System (DSS) for organic N management has been proposed earlier that subdivides ORs in four classes depending on their N, lignin, and soluble polyphenol contents. To validate this DSS, a 28-d aerobic incubation experiment was initiated with 32 ORs, mostly crop and tree residues, applied to a sandy loam soil. The ORs contained 1.4 to 53.2 g kg^{-1} of N, 25 to 295 g kg^{-1} of lignin, and 4 to 148 g kg^{-1} of soluble polyphenols. In vitro dry matter digestibility (IVDMD) ranged from 70 to 820 g kg^{-1}. After 28 d, CO_2–C production varied between 199 and 905 mg CO_2–C kg^{-1} soil, and mineral N contents ranged from 5 to 109 mg N kg^{-1} soil. Based on N mineralization data, three classes of ORs were evident: Class A with N release > 0, Class B with N release approximately 0, and Class C with N release < 0 (N immobilization). Criteria to separate those classes were based on the OR N and polyphenol content and cut-off values between the classes agreed well with those proposed in the original DSS. For Class A ORs, N mineralization was negatively related to their lignin/N ratio (except for *Gliricida* residues) and for Class C ORs, N immobilization was positively related to their N content. Short-term mineralization data supported the existence of three classes of ORs instead of four originally proposed by the DSS. However, ORs also govern other functions, operating in the medium to long term, and for these functions, the original four-class concept may be proven valid.

Organic resources play a critical role in maintaining tropical soil fertility and are an integral part of the currently adopted Integrated Soil Fertility Management (ISFM) research and development paradigm for tropical soil fertility research (Defoer and Budelman, 2000; Vanlauwe et al., 2002a). In the short term, ORs release nutrients, may enhance soil moisture conditions (Barrios et al., 1997), or improve the soil available P status (Nziguheba et al., 2000). In the long term, continuous inputs of ORs influence the levels of soil organic matter and the quality of some or all of its pools (Vanlauwe et al., 1998; Cadisch and Giller, 2000). Integrated Soil Fertility Management recognizes that both mineral inputs and ORs are required for sustainable tropical agriculture, partly because either of those usually is in short supply for sole application, but also because the combined application of mineral inputs and ORs possibly generates added benefits, for example, in terms of extra crop yield or extra C build-up (Palm et al., 1997; Vanlauwe et al., 2001).

Unlike mineral fertilizers, the release dynamics of plant available nutrients from ORs vary widely and are less predictable. Such uncertainties may hinder the most efficient use of these ORs or even their adoption by small-scale farmers. A range of quality characteristics has been found to affect the decomposition and mineralization process of ORs. Originally, the C/N ratio was seen as a good predictor of decomposition and N availability (Waksman and Tenney, 1928). Subsequently, Vallis and Jones (1973) reported that soluble polyphenols affect N mineralization dynamics of ORs. Melillo et al. (1982) showed that the N and lignin content of hardwood leaf litter residues significantly affected their decomposition; while Handayanto et al. (1994) showed that the content of soluble polyphenols that were actively binding proteins was better related to decomposition than the total soluble polyphenol content. The superiority of certain indices over others for predicting N-mineralization has perhaps been more related to the types of organic materials being studied (crop residues, temperate tree leaf litter, or fresh leaves—Palm and Rowland, 1997) or the range of resource quality used in the study (Constantinides and Fownes, 1994) rather than to real differences in the controls on decomposition and N release patterns. For instance, when only looking at cereal residues, soluble polyphenols are likely not going to be included in quality-mineralization relationships as such ORs usually contain <10 g kg^{-1} polyphenols. The different parameters for predicting N release have been added or modified as different plant materials with more diverse resource quality parameters have been studied.

Although ORs are not new to tropical agriculture, a seminal synthesis on organic matter management and decomposition was written only in 1979 (Swift et al., 1979). The Organisms-Physical environment-Quality framework for organic matter decomposition and nutrient release, proposed by Swift et al. (1979) was later translated into hypotheses underlying management options to improve nutrient acquisition and crop growth (Swift, 1984, 1985, 1986). During the 1990s, the formulation of the research hypotheses related to residue quality and N release led to a substantial amount of projects aiming at testing these hypotheses. Based on this information,

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Abbreviations: ADF, acid detergent fiber; BSA, bovin serum albumin; DSS, decision support system for organic N management; ISFM, Integrated Soil Fertility Management; IVDMD, in vitro dry matter digestibility; LSD, least significant difference; OR, organic resource; ORD, organic resource database; PBC, protein-binding capacity; PP, polyphenols; SED, standard error of the difference.

Palm et al. (2001) compiled the Organic Resource Database (ORD) that currently contains information on quality parameters of plant materials, including macronutrient, lignin and polyphenol contents of fresh leaves, litter, stems and/or roots from almost 300 species found in tropical agroecosystems (Tropical Soil Biology and Fertility Institute, 1997). Following analysis of a substantial number of laboratory-based N-mineralization studies using a wide range of ORs, Palm et al. (2001) proposed a conceptual DSS. Their DSS proposed four classes of ORs, each having specific management options. Class I contains materials with high N (>25 g kg^{-1}), low soluble polyphenol (<40 g kg^{-1}), and low lignin (<150 g kg^{-1}) content and is proposed to be applied directly to a growing crop. Classes II and III ORs are proposed to be mixed with either fertilizer or Class I ORs as these classes have either a high N (>25 g kg^{-1}) and a high polyphenol (>40 g kg^{-1}) or a high lignin content (>150 g kg^{-1}) (Class II), or a low N (<25 g kg^{-1}), a low polyphenol (<40 g kg^{-1}), and a low lignin content (<150 g kg^{-1}) (Class III). Class IV ORs have a low N (<25 g kg^{-1}) and a high lignin content (>150 g kg^{-1}) and are advised to be applied as surface mulch. Note that in this manuscript, the classes proposed by Palm et al. (2001) are referred to as Class I, II, III, and IV, while the classes developed based on the data in this manuscript are referred to as Classes A, B, and C. Validation of the N availability patterns relative to crop demand and productivity that is implicit in the above conceptual model is a necessary step in converting the DSS into a robust OR management tool. It is thereby necessary to use a large and well-chosen range of ORs covering the complete OR quality spectrum and to measure resource quality using standardized approaches. One of the commonly used assessments for C and N mineralization is an aerobic incubation under controlled conditions for a number of weeks. Recently, some efforts have been made to shorten this procedure by adapting in vitro approaches to determine fodder digestibility, commonly used by animal nutritionists (Tian et al., 1996; Cobo et al., 2002). A validation of the DSS should cover the currently accepted (incubation, IVDMD assay), standardized approaches for assessing OR quality and C and N mineralization, as the final aim of OR quality assessment is to relate OR characteristics with specific OR-driven functions.

The objectives of this work were (i) to explore relationships between the aerobic incubation and the in vitro digestibility approach for assessing short-term OR C and N mineralization dynamics, (ii) to evaluate relationships between short-term decomposition dynamics and OR characteristics, and (iii) to validate the conceptual model proposed by Palm et al. (2001), thereby using a set of plant materials covering a wide range of biochemical properties and analyzed using standard procedures.

MATERIALS AND METHODS

Plant Materials Used

The selection of 32 ORs, collected from different parts of Kenya (Table 1), was based on prior knowledge of OR quality parameters, as documented in the ORD and belonging to Classes I to IV (Palm et al., 2001). Some reference to plant age is also mentioned as canopy age of hedgerow trees was observed to affect the quality of its prunings (Vanlauwe et al., 2001). Attempts were also made to select ORs that are potentially available as sources of organic matter in Kenyan farming systems (Lauriks et al., 1999), and consisted of crop residues and various parts of tree prunings. One farmyard manure sample and one sawdust sample were also included.

Residue Quality Determination

Materials were oven dried at 35°C till constant weight to avoid alteration of the polyphenol profile (Dzowela et al., 1995) and ground to pass through a 1-mm sieve. Plant nutrients (N, P, K, Ca, and Mg) were analyzed after complete oxidation of the plant materials by Kjedahl digestion (Anderson and Ingram, 1993). Nitrogen was determined from 5 mL of aliquot of the digestion mixture using an auto analyzer (Skalar Analytical, BV, The Netherlands) while K was determined through flame photometry (Okalebo et al., 2002). Phosphorus was measured using a colorimetric approach and Ca and Mg with an atomic absorption spectrophotometer (Okalebo et al., 2002). Total C of the ORs was measured using potassium dichromate (Anderson and Ingram, 1993). Water-soluble C was obtained by wet oxidation, using potassium dichromate, of an organic matter extract, obtained after extracting 30 mg of plant material with 20 mL of water for 1 h at 100°C (ICRAF, 1995). The total soluble polyphenol content was quantified by the Folin-Ciocalteu reagent, against a tannic acid standard after extraction of 0.1 g of plant material with 50 mL of a 50% (v/v) methanol-water mixture, while the lignin content was measured through the acid detergent fiber (ADF) route (Anderson and Ingram, 1993). Finally, the protein binding capacity of soluble polyphenols was determined following Handayanto et al. (1994).

Aerobic Incubation

A sandy-loam soil (Kandiustult) was used for the incubation experiment, sampled from the 0- to 15-cm layer of a farmer's field in Teso, Western Kenya. The soil had the following characteristics: 4.8 g kg^{-1} organic C, 0.37 g kg^{-1} total N, 0.81 $cmol_c$ kg^{-1} exchangeable Ca, 0.16 $cmol_c$ kg^{-1} exchangeable Mg, 0.15 $cmol_c$ kg^{-1} exchangeable K, 0.44 $cmol_c$ kg^{-1} exchangeable acidity, 780 g kg^{-1} sand, 80 g kg^{-1} silt, 140 g kg^{-1} clay, and a pH in water of 5.4. The soil was moistened with distilled water to attain 40% water-holding capacity, determined after allowing saturated soil to drain for 24 h at room temperature. The soil was then kept at room temperature for 2 wk before incubation. Fifty grams oven-dry weight equivalent of soil was thoroughly mixed with the ORs at a rate equivalent to 5 Mg ha^{-1} dry weight basis (178.6 mg dry matter per 50 g dry soil) and placed in 60-mL bottles. Control soils did not receive any ORs. The bottles were placed in incubation jars (250 mL glass bottles) containing 10 mL of distilled water to help maintain the moisture content of the soil-OR mixture during the incubation period and a vial with 10 mL of 0.5 *M* NaOH to trap CO_2 released during decomposition and mineralization of the ORs. The jars were tightly sealed and kept in the dark at 25°C. Sufficient jars were set up to allow for four destructive sampling times, three times replicated (12 jars per treatment). The jars were arranged in a completely randomized design. Jars without soil added were used as blanks. After 3, 7, 14, and 28 d, CO_2 trapped in the NaOH solution was determined by titrating the excess base with 0.5 *M* HCl (ICRAF, 1995) and all NaOH traps were replaced to avoid saturation of the NaOH solution (except at Day 28). On the same dates, three jars per treatment were destructively sampled for mineral N determination. Mineral N was also determined at the beginning of the experiment. Ammonium N and NO_3^-–N in the soil were

Table 1. Description of the organic resources (ORs) used in the decomposition study. All materials were collected in Kenya. Leaflets did not contain the petioles of composite leaves while twigs had a diameter of <10 mm.

No.	Species	Site (division, district)	Source of materials
1	*Zea mays* L.	Nyabeda (Yala, Siaya)	Stover collected from physiologically mature maize from farmers' fields
2	*Croton megalocarpus* Hutch.	Kwisero (Kwesiro, Mumias-Butere)	Leaves collected from mature plants within farmers' fields
3	*Senna spectabilis* (DC.) H. S. Irwin & Barneby	Nyabeda (Yala, Siaya)	Leaflets collected from mature plants within farmers' fields
4	*Lantana camara* L.	Khisero (Khisero, Mumias-Butere)	Leaves collected from mature and young shrubs growing along the road
5	*Calliandra calothyrsus* Meisn.	Khisero (Khisero, Mumias-Butere)	Leaflets picked from coppicing plants on farmers' fields
6	*Senna siamea* (Lam.) H. S. Irwin & Barneby	Kwisero (Kwesiro, Mumias-Butere)	Leaflets picked from mature plants on farmers' fields
7	*Crotalaria ochroleuca* G. Don	Ochinga (Luanda, Vihiga)	Leaflets picked from young and mature plants on farmers' fields
8	*Crotalaria grahamiana* Wight & Arn.	Msinde (Luanda, Vihiga)	Leaflets picked from young and mature plants on farmers' fields
9	*Tithonia diversifolia* (Hemsl.) A. Gray	Nyabeda (Yala, Siaya)	Leaves picked from young and mature plants on farmers' fields
10	*Gliricidia sepium* (Jacq.) Kunth ex Walp.	Nyabeda (Yala, Siaya)	Leaflets picked from coppicing plants on experimental plots
11	*Gliricidia sepium*	Machakos (Central, Machakos)	Leaflets picked from mature trees in hedgerows
12	*Senna siamea*	Machakos (Central, Machakos)	Leaflets picked from coppicing plants, recovering from fire
13	*Flemingia macrophylla* (Willd.) Merr.	Machakos (Central, Machakos)	Leaflets collected from a mature experimental plot
14	*Senna spectabilis*	Machakos (Central, Machakos)	Leaflets collected from a mature experimental plot
15	*Calliandra calothyrsus*	Embu (Central, Embu)	Leaves picked from a mature provenance trial (Embu provenance)
16	*Calliandra calothyrsus*	Embu (Central, Embu)	Leaflets picked from a mature provenance trial (Embu provenance)
17	*Calliandra calothyrsus*	Embu (Central, Embu)	Leaves picked from a mature provenance trial (Patalul provenance)
18	*Calliandra calothyrsus*	Embu (Central, Embu)	Leaflets picked from a mature provenance trial (Patalul provenance)
19	*Calliandra calothyrsus*	Embu (Central, Embu)	Leaves picked from a mature provenance trial (San Ramon provenance)
20	*Calliandra calothyrsus*	Embu (Central, Embu)	Leaflets picked from a mature provenance trial (San Ramon provenance)
21	*Saccharum officinarum* L.	Nairobi (Westlands, Nairobi province)	Stover from mature sugarcane along the road
22	*Lantana camara*	Nairobi (Westlands, Nairobi province)	Leaves collected from a coppicing hedge along the road
23	*Lantana camara*	Nairobi (Westlands, Nairobi province)	Stems collected from a coppicing hedge along the road
24	Cattle manure	Maseno (Maseno, Kisumu)	Cattle manure collected from the Maseno Veterinary Farm
25	*Tithonia diversifolia*	Nairobi (Westlands, Nairobi province)	Leaves collected from a coppicing hedge along the road
26	*Gliricidia sepium*	Muguga (Kikuyu, Kiambu)	Stems from a mature seed orchard
27	*Senna spectabilis*	Muguga (Kikuyu, Kiambu)	Leaves from a mature seed orchard
28	*Sesbania sesban* (L.) Merr.	Muguga (Kikuyu, Kiambu)	Leaves from a mature seed orchard
29	*Gliricidia sepium*	Muguga (Kikuyu, Kiambu)	Leaflets from a mature seed orchard
30	*Sesbania sesban*	Muguga (Kikuyu, Kiambu)	Stems from a mature seed orchard
31	*Eucalyptus saligna* Sm.	Muguga (Kikuyu, Kiambu)	Leaf litter from a mature seed orchard
32	*Eucalyptus saligna*	Muguga (Kikuyu, Kiambu)	Saw dust collected from a carpenter shop

determined after extracting 20 g of fresh soil with 100 mL of 2 *M* KCl (Dorich and Nelson, 1984). Nitrate N was determined through Cd reduction of NO_3^-–N to NO_2^-–N and the NO_2^-–N concentration was determined colorimetrically at 525 nm while NH_4^+–N was determined colorimetrically at 655 nm (ICRAF, 1995).

In Vitro Dry Matter Digestibility Assay

In vitro dry matter digestibility is a laboratory assay commonly used as OR quality index for animal feed by animal nutritionists (Harris, 1970). This method includes two consecutive digestion phases. During the first digestion phase, ORs were incubated for a 48-h period at 39°C, under anaerobic conditions, with rumen liqueur and the obligatory anaerobe microorganisms that inhabit the rumen. Rumen liqueur was collected from two fistulated steers that grazed on star grass [*Cynodon plectostachyus* (K. Schum.) Pilg.] and fed once a week on soybean [*Glycine max* (L.) Merr.] meal. This phase was followed by a 24-h acid–pepsin digestion phase that maintained the same temperature and anaerobic conditions. Plant material remaining after the 72-h incubation was collected, oven dried at 105°C for 12 h, and weighed. Ash contents were determined by heating residual plant materials at 550°C for 2 h. Control bottles followed exactly the same procedure but were incubated without plant material. In vitro dry matter digestibility was calculated on an ash-free basis as:

$$\text{IVDMD (g kg}^{-1}) = \left(1 - \frac{\text{weight dry plant residue} - \text{weight of blank}}{\text{weight of original plant material}}\right)1000 \quad [1]$$

Data Analysis

The proportional amounts of C and N mineralized were calculated as:

Table 2. Selected characteristics of organic resources used in the decomposition study.†

No.	Species	Plant part	C	N	C/N	P	Ca	Mg	K	Sol C	PP	PBC	Lignin	Cmin	Nmin	IVDMD
			— g kg^{-1} —			g kg^{-1}								%		mg BSA (g DM)$^{-1}$
1	*Zea mays*	Stover	413	5.9	70.9	0.3	3.3	3.4	8.0	48	10.6	15	46.2	36.1	−107.5	559
2	*Croton megalocarpus*	Leaves	416	33.8	12.3	1.4	15.4	5.7	19.6	75	30.9	36	86.8	42.0	21.8	588
3	*Senna spectabilis*	Leaflets	443	41.8	10.6	2.2	16.1	2.1	15.6	119	27.3	19	82.0	45.1	18.1	609
4	*Lantana camara*	Leaves	410	34.5	11.9	2.1	15.3	4.4	22.6	84	61.5	48	116.0	27.1	1.4	574
5	*Calliandra calothyrsus*	Leaflets	445	40.9	10.9	1.6	13.8	5.5	6.0	76	95.4	164	88.4	25.0	3.5	359
6	*Senna siamea*	Leaflets	449	29.3	15.3	1.3	23.9	1.3	5.3	98	72.3	24	112.7	34.0	−2.1	600
7	*Crotalaria ochroleuca*	Leaflets	455	53.2	8.6	2.4	9.1	4.4	15.7	104	31.3	22	35.5	43.7	41.6	824
8	*Crotalaria grahamiana*	Leaflets	378	34.2	11.1	1.6	18.4	5.3	6.4	101	27.7	21	48.5	56.8	21.1	747
9	*Tithonia diversifolia*	Leaves	398	32.9	12.1	2.7	19.5	4.8	33.6	92	59.7	29	81.6	35.7	5.9	529
10	*Gliricidia sepium*	Leaflets	437	37.9	11.5	1.6	18.9	8.1	9.0	138	28.7	29	107.7	44.8	30.0	625
11	*Gliricidia sepium*	Leaflets	405	35.8	11.3	1.6	32.3	7.3	14.4	119	25.6	21	156.8	43.3	31.1	632
12	*Senna siamea*	Leaflets	436	19.9	21.8	1.0	32.5	2.8	6.2	119	81.4	22	104.5	36.1	−17.4	619
13	*Flemingia macrophylla*	Leaflets	404	29.0	14.0	1.8	16.4	4.1	4.6	114	86.3	171	161.1	26.7	−3.0	322
14	*Senna spectabilis*	Leaflets	465	34.2	13.6	1.7	18.8	1.8	12.7	129	36.8	12	96.4	39.9	6.4	596
15	*Calliandra calothyrsus*	Leaves	438	30.3	14.5	1.2	13.5	4.7	4.9	114	140.1	295	97.8	21.2	1.7	375
16	*Calliandra calothyrsus*	Leaflets	419	35.3	11.9	1.3	18.2	5.8	5.0	92	100.4	118	145.3	21.2	9.4	384
17	*Calliandra calothyrsus*	Leaves	464	30.3	15.3	1.1	9.1	4.0	6.1	128	144.8	288	62.1	21.8	−3.9	389
18	*Calliandra calothyrsus*	Leaflets	463	31.0	14.9	1.0	8.9	3.5	4.9	120	147.7	322	120.9	19.3	−4.0	372
19	*Calliandra calothyrsus*	Leaves	451	26.1	17.3	0.8	9.9	4.1	4.8	104	122.6	280	129.3	20.8	−3.4	334
20	*Calliandra calothyrsus*	Leaflets	445	32.0	13.9	1.0	12.3	3.9	4.9	95	94.6	198	157.9	23.2	5.3	346
21	*Saccharum officinarum*	Stover	402	12.2	33.4	1.5	2.8	1.0	21.8	49	15.1	19	47.2	40.7	−42.9	541
22	*Lantana camara*	Leaves	437	45.1	9.7	3.3	14.9	6.6	25.9	85	51.5	13	62.0	36.7	25.7	708
23	*Lantana camara*	Stems	426	9.5	45.0	0.7	3.2	1.1	13.3	31	14.8	21	164.0	24.9	−60.6	212
24	Cattle manure	NA†	370	25.4	14.6	6.2	10.8	6.8	35.6	37	10.5	48	172.7	17.9	3.3	268
25	*Tithonia diversifolia*	Leaves	377	42.5	8.9	2.6	19.3	4.1	40.3	95	48.5	24	45.6	42.8	33.8	617
26	*Gliricidia sepium*	Stems	421	16.4	25.7	0.9	9.7	3.6	26.7	50	13.0	26	204.4	24.4	7.3	311
27	*Senna spectabilis*	Leaves	455	45.8	10.0	2.3	13.3	1.7	20.4	99	18.9	26	112.7	33.4	14.4	560
28	*Sesbania sesban*	Leaves	370	44.8	8.3	2.4	53.4	4.9	11.3	151	23.0	30	25.4	58.3	35.3	765
29	*Gliricidia sepium*	Leaflets	407	37.8	10.8	1.6	18.5	4.8	21.2	116	35.0	34	166.7	36.2	21.1	545
30	*Sesbania sesban*	Stems	444	8.2	54.4	0.4	6.2	1.2	7.6	32	8.4	25	150.9	36.8	−86.6	228
31	*Eucalyptus saligna*	Leaf litter	461	10.3	44.8	0.3	9.5	1.3	4.3	89	108.3	183	236.8	21.5	−54.9	260
32	*Eucalyptus saligna*	Saw dust	486	1.4	348.8	0.1	0.8	0.2	0.5	14	17.4	20	294.5	3.7	−90.3	70

† BSA = bovin serum albumin; Cmin = C mineralization after 28 d; IVDMD = in vitro dry matter digestibility; NA = not applicable; Nmin = N mineralization/immobilization after 28 d; PBC = protein binding capacity; PP = soluble polyphenols; Sol C = soluble C.

$$\text{C mineralization (\%)} = \left(\frac{\text{CO}_2\text{-C in treated soil} - \text{CO}_2\text{-C in control soil}}{\text{C added to the treated soil}}\right)100 \quad [2]$$

$$\text{N mineralization (\%)} = \left(\frac{\text{Mineral N in treated soil} - \text{Mineral N in control soil}}{\text{N added to the treated soil}}\right)100 \quad [3]$$

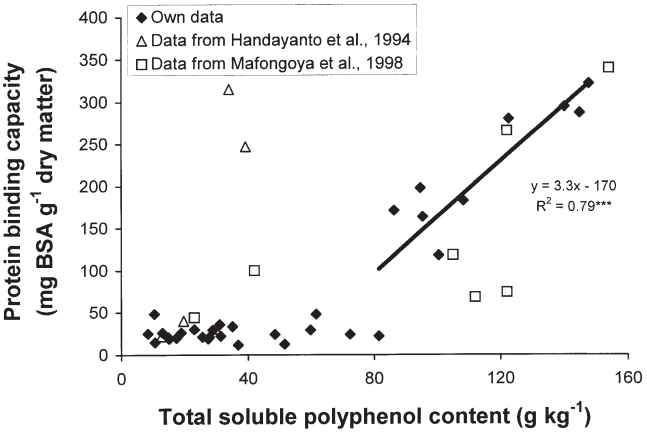

Fig. 1. Relationship between the protein binding capacity (PBC) and the total soluble polyphenol content of the used organic resources (ORs). The regression line was calculated for data points with >80 g kg^{-1} of polyphenols. Data presented by Handayanto et al. (1994) and Mafongoya et al. (1998) are superimposed. * Represents significance at the 0.1% level. Note that the dry matter/methanol ratio for extraction of the soluble polyphenols was 0.75 g dry matter/50 mL methanol for Handayanto et al. (1994) and 0.1 g dry matter/50 mL methanol for Mafongoya et al. (1998), the latter using a similar ratio as in this paper.**

Carbon and N mineralization data were analyzed using mixed modeling procedures of the MIXED procedure of SAS (SAS Institute, 1992), for each time of analysis separately, and standard errors of the difference (SED) were calculated using the LSMEANS option. In the mixed model analysis, 'treatment' was used as a fixed factor and 'replicate' as a random factor. Statistically significant means were separated with pairwise *t* tests, using the PDIFF option of the LSMEANS (least square means) procedure.

Single and multiple regression (STEPWISE method) techniques (SAS Institute, 1985) were used to relate decomposition dynamics, averaged over all replicates, to various OR characteristics. In the multiple regression calculations, independent variables entered the regression model at the 0.15 significance level.

RESULTS

Residue Quality

The ORs contained between 1.4 and 53.2 g kg^{-1} of N, 25 and 295 g kg^{-1} of lignin, and 4 and 148 g kg^{-1} of soluble polyphenols (Table 2). The protein binding capacity (PBC) ranged between 12 and 322 mg bovin serum albumin g^{-1} dry matter. The PBC was linearly related (R^2 = 0.79) to total extractable polyphenols for ORs with soluble polyphenol content above 80 g kg^{-1} (Fig. 1). For ORs with less polyphenols, the PBC appeared to be low and independent of total soluble polyphenol content.

Residue Decomposition Dynamics

Cumulative CO_2–C production after 28 d varied between 199 (sawdust) and 905 mg CO_2–C kg^{-1} soil (*Ses-*

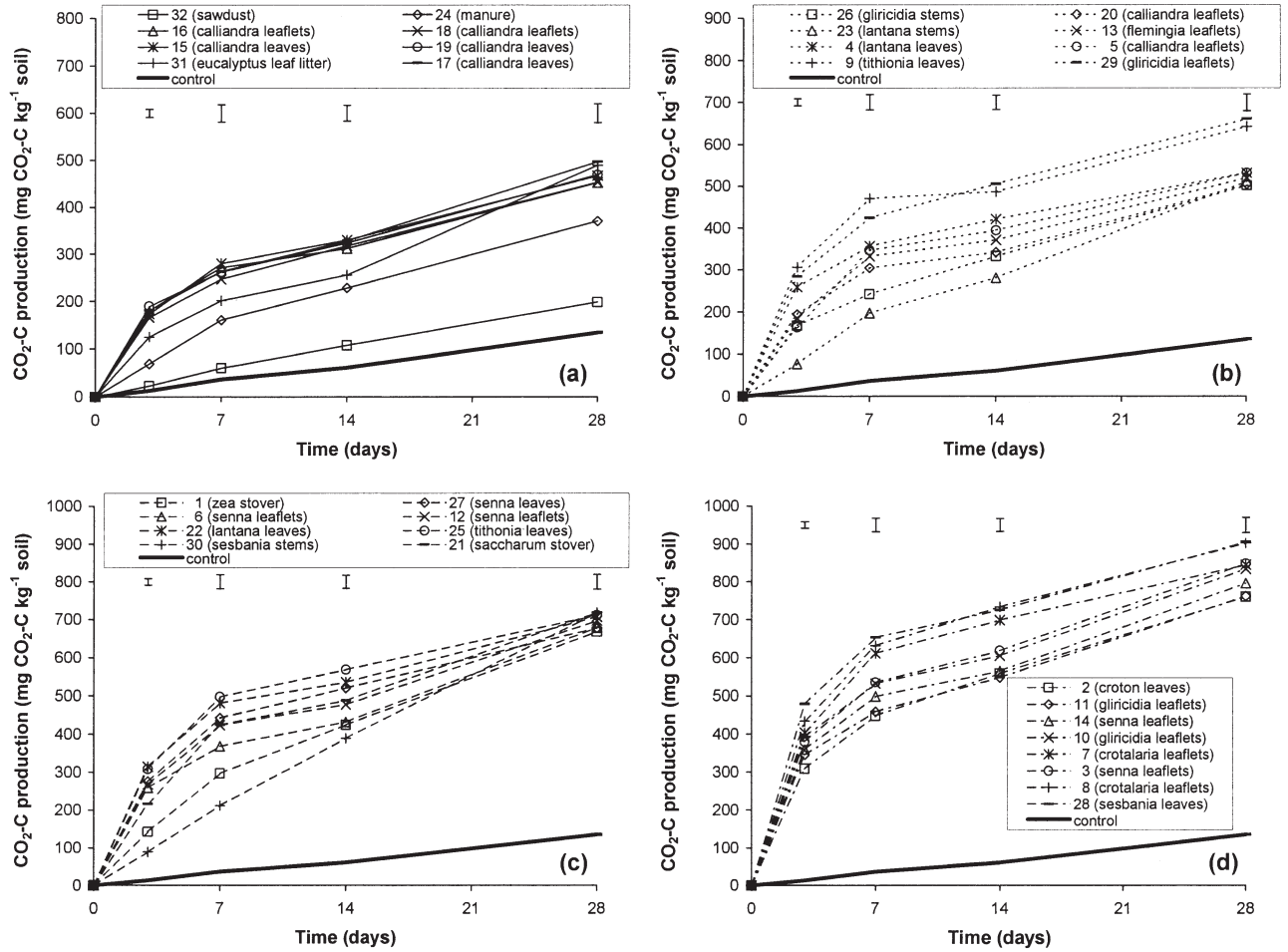

Fig. 2. Cumulative CO_2–C production for the various treatments. Figures 2a, 2b, 2c, and 2d each contain the C mineralization data from eight organic resources (ORs) and the control soil. Total CO_2–C production increases from Fig. 2a to Fig. 2d, resulting in different *y*-axis ranges. Error bars are standard errors of the difference, calculated for each sampling time.

bania sesban leaves) (Fig. 2). The control soil produced 135 mg CO_2–C kg^{-1} soil during the same period of time. Most *Calliandra* residues decomposed relatively slowly while the *Gliricida* leaf or leaflet residues produced medium to large amounts of CO_2–C (Fig. 2). In general, most CO_2–C release curves exhibited an initial flush in CO_2–C evolution, followed by a period with a relatively constant CO_2–C production rate between Days 7 and 28, except for some ORs that produced relatively higher amounts of CO_2–C during the later stages of decomposition after an initial low activity (Fig. 2). Pearson correlation coefficients among the cumulative proportions of added C mineralized at various sampling dates varied between 0.88 and 0.97 (data not shown).

Mineral N contents (nitrate N and ammonium N) at 28 d varied between 5 (*Sesbania* stems) and 109 mg N kg^{-1} soil (*Sesbania* leaves) (Fig. 3). Of the 32 ORs used, 12 resulted in less soil mineral N after 28 d than the unamended control soil, which contained 30 mg N kg^{-1} soil. When expressing N release as a proportion of the total amount of N added, 7 ORs had negative values significantly lower than 0 while 12 ORs had values significantly above 0 (Fig. 4). There appeared to be three classes of ORs (Fig. 4), one class with N-mineralization values significantly above 0 (Class A), one class with values not different from 0 (Class B), and a third class with values significantly below 0 (Class C). Pearson correlation coefficients among the percentages of applied N mineralized at the various sampling dates varied between 0.82 and 0.98 (data not shown).

In vitro dry matter digestability ranged between 70 g kg^{-1} (*Eucalyptus* sawdust) and 820 g kg^{-1} (*Crotalaria ochroleuca* leaflets) (Table 2). A highly significant linear relationship was observed between the cumulative C release at 28 d and the IVDMD (Fig. 5). In contrast to the C mineralization the relationship between IVDMD and N mineralization was more complex. Organic resources that exhibited a net N release above the control (positive proportion of N mineralized) after 28 d showed a 1:1 relationship with IVDMD values although the relationship became increasingly uncertain at lower values. For ORs having negative N mineralization values (soil mineral N immobilization) two trends could be observed: (i) resources with a low N, polyphenol and lignin content appeared to have IVDMD values ranging from 500 to 600 g kg^{-1}, independent of the N mineralization data (Fig. 5) and (ii) resources having a low N content and either a high polyphenol or a high lignin content showed IVDMD values decreasing with the proportional N release values (Fig. 5).

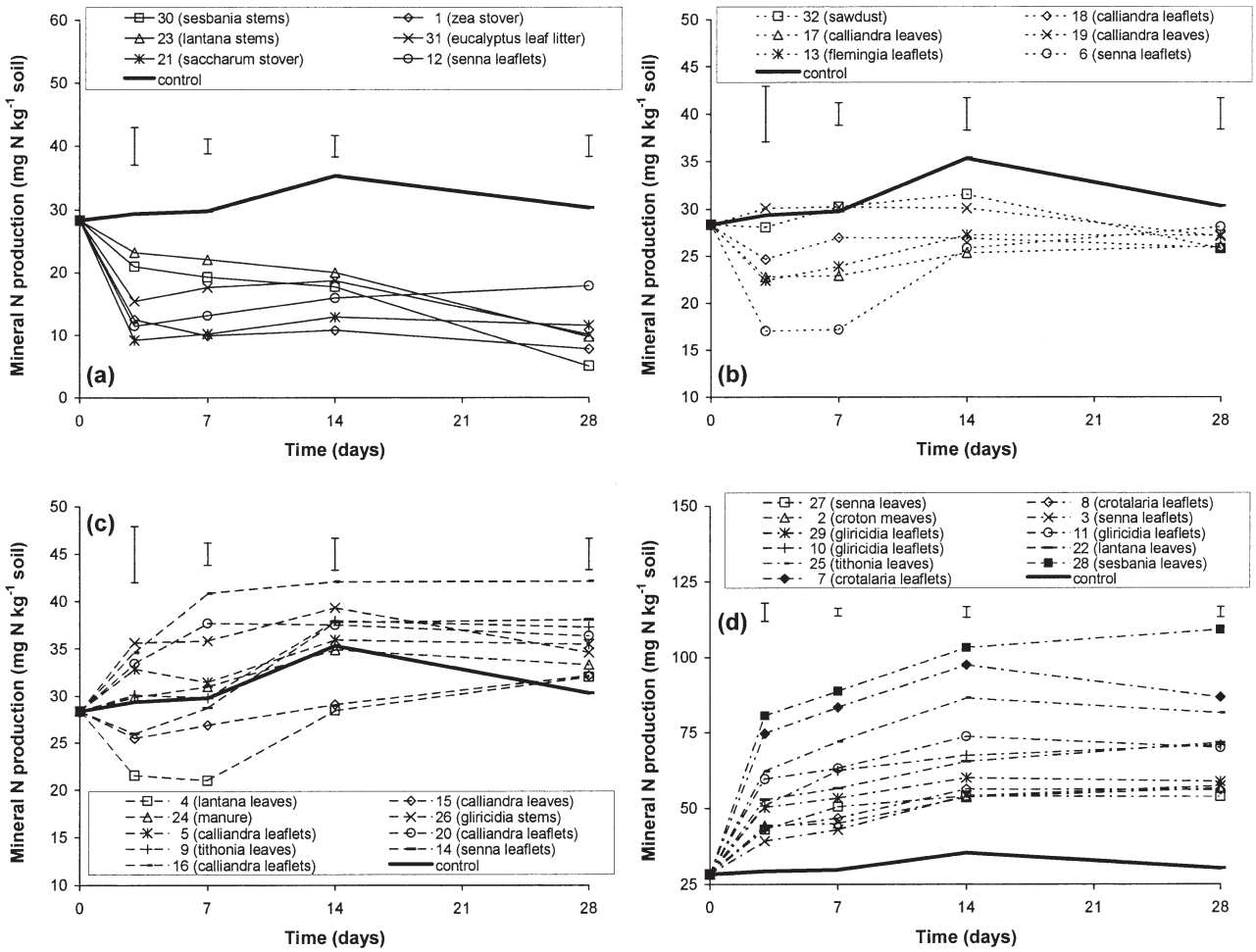

Fig. 3. Mineral N production for the various treatments. Figure 3a presents data from organic resources that have significantly lower levels of mineral N than the control soil at Day 28; Fig. 3b and 3c present data from organic resources that had slightly lower and slightly higher, respectively, amounts of mineral N than the control soil at Day 28, and Fig. 3d presents data from the organic resources that produced a significantly higher amount of mineral N than the control soil at Day 28. Error bars are standard errors of the difference, calculated for each sampling time.

Relationships between Decomposition Dynamics and Organic Resource Quality

The ratio of the amount of CO_2–C released after 3 d over the amount released after 28 d was positively related to the soluble C content of the ORs up to about 50% proportional C release (Fig. 6).

Lignin, polyphenol, and soluble C content of the ORs explained 86% of the variation in cumulative C mineralization (Table 3). In vitro dry matter digestibility was related to lignin, polyphenol, and soluble C content, explaining 83% of its variation. Cumulative N mineralization was related to N, C, lignin, and soluble C content of the ORs, although N content on its own explained already 76% of the variation (Table 3). When considering only Class C data (Fig. 4), a highly significant linear relationship was observed between N-immobilization and the N content of the ORs (Fig. 7a). For Class A data (Fig. 4), no significant relationship between N mineralization and any specific OR quality parameter was observed. Excluding the *Gliricidia* samples, however, N mineralization was linearly related with the lignin/N ratio of the ORs (Fig. 7b). Note that for Class A ORs, no significant correlations were observed between lignin and polyphenol content, nor between lignin/N and polyphenol/N ratio (data not shown).

DISCUSSION

When considering short-term N release from ORs, having three rather than the original four classes, proposed by Palm et al. (2001), appears to be sufficient. In the current work, ORs of Class A (Fig. 4) had >34 g kg^{-1} of N, <52 g kg^{-1} of soluble polyphenols (except Sample 16 of *Calliandra* with 100 g kg^{-1} polyphenols), and <170 g kg^{-1} of lignin (Fig. 4). This is in close agreement with the original threshold values of 25 g kg^{-1} N, 40 g kg^{-1} polyphenols, and 150 g kg^{-1} lignin, for Class I residues proposed by Palm et al. (2001). Organic resources belonging to the current Class B had >26 g kg^{-1} of N, >37 g kg^{-1} of polyphenols, and <130 g kg^{-1} of lignin (Fig. 4). Again these values correspond closely with two of the threshold values for the Class II resources (25 g kg^{-1} of N and 40 g kg^{-1} of polyphenols) proposed by Palm et al. (2001). Although, theoretically,

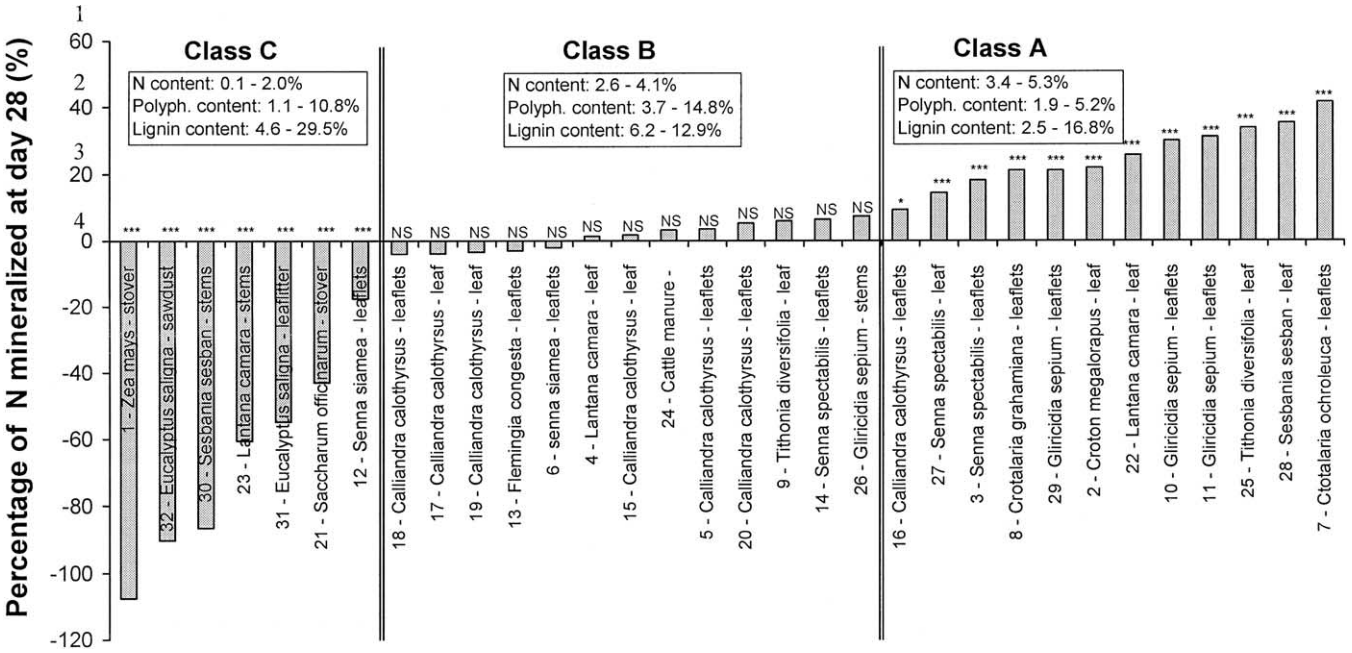

Fig. 4. The percentage of added organic resource (OR)-N mineralized after 28 d. *, *, and NS represent significance at the 0.1% and the 5% level and not significant, respectively, as calculated with the LSMEANS option of the MIXED procedure (SAS, 1992). The vertical bars delineate three groups of ORs: a first group that has values significantly <0, a second group with values not different from 0, and a third group with values significantly larger than 0. The range of N, polyphenol, and lignin contents presented for the middle group, excludes Samples 24 (cattle manure: 25 g kg^{-1} of N, 11 g kg^{-1} of polyphenols and 173 g kg^{-1} of lignin) and 26 (*Gliricidia* stems: 16 g kg^{-1} of N, 13 g kg^{-1} of polyphenols and 204 g kg^{-1} of lignin).**

Class II ORs have a lignin content > 150 g kg^{-1} and/or a polyphenol content >40 g kg^{-1}, 10 of the 14 ORs used in this study that were grouped as Class II or Class B have a lignin content < 150 g kg^{-1} and a polyphenol content > 40 g kg^{-1}. When screening the complete ORD (Tropical Soil Biology and Fertility Institute, 1997), 68% of the Class II resources have similar properties, indicating that ORs with high N and high lignin content are less common. Organic resources of Class C were an amalgamation of Class III and IV ORs proposed by Palm et al. (2001), as their only quality parameter distinguishing them from the current Class A and B is their low N content (<20 g kg^{-1}), resulting in immobilization of soil-derived N (Fig. 4).

The three classes of ORs presented in Fig. 4 are mainly distinguished by their N and polyphenol contents as the ranges of lignin contents of the various classes overlap substantially (Fig. 4). While Palm et al. (2001) used lignin content to distinguish between Classes III and IV, in this work these classes were found to be merged into a single Class C. Short-term N mineralization has been observed earlier to be driven by N and polyphenol contents (Palm and Sanchez, 1991). Shepherd et al. (2003) similarly concluded, after reanalyzing the original data used by Palm et al. (2001), that lignin concentration had no predictive power in classifying N release once N concentration was taken into account. However, when zooming in on Class A, lignin was observed to influence N release (Fig. 7b). Lignin contents did not impact on N immobilization for Class C residues perhaps because the available C content of these ORs was sufficiently high to maintain microbial activity within a 28-d period (Vanlauwe et al., 1996). When looking at impacts in the medium to long term, however, lignin may override the influence of N and polyphenols (Palm and Rowland, 1997).

Note that the above framework was not valid for the cattle manure (Sample 24) and the *Gliricidia* stem (Sample 26) and leaflet (Samples 10, 11, and 29) treatments. The two former ORs had a relatively low N content (25 and 16 g kg^{-1}, respectively) and a relatively high lignin content (173 and 204 g kg^{-1}, respectively) but failed to immobilize substantial amounts of soil N after 28 d of incubation. Vanlauwe et al. (2002b) similarly showed that animal manure samples did not follow the predicted release patterns. Manure samples are known to behave differently from plant materials as the former have gone through a decomposition phase when passing through the digestive system of the cattle (Delve et al., 2001), thus rendering the C less available and resulting in relatively less N immobilization. The *Gliricidia* leaf materials used in this study (Samples 10, 11, and 29) released substantially more mineral N than would be expected from their relatively high lignin/N ratio (Fig. 7b). The relatively higher availability of N from all *Gliricidia* residues compared with the other ORs can be caused by a lack of complete digestion of the lignin-like fraction during the ADF or H_2SO_4 extraction step. When consulting the ORD, the average N content of all *Gliricidia* leaf residues is 35 g kg^{-1} (±7 g kg^{-1}), their lignin content 114 g kg^{-1} (±46 g kg^{-1}), and their polyphenol content 19 g kg^{-1} (±8 g kg^{-1}). Although four of the 25 *Gliricidia* leaf lignin entries contain lignin contents above 150 g kg^{-1}, the lignin contents of the *Gliricidia* leaflet residues in this report appear to be on the high side (108, 157, 167 g kg^{-1}), more so because leaflets usually contain less

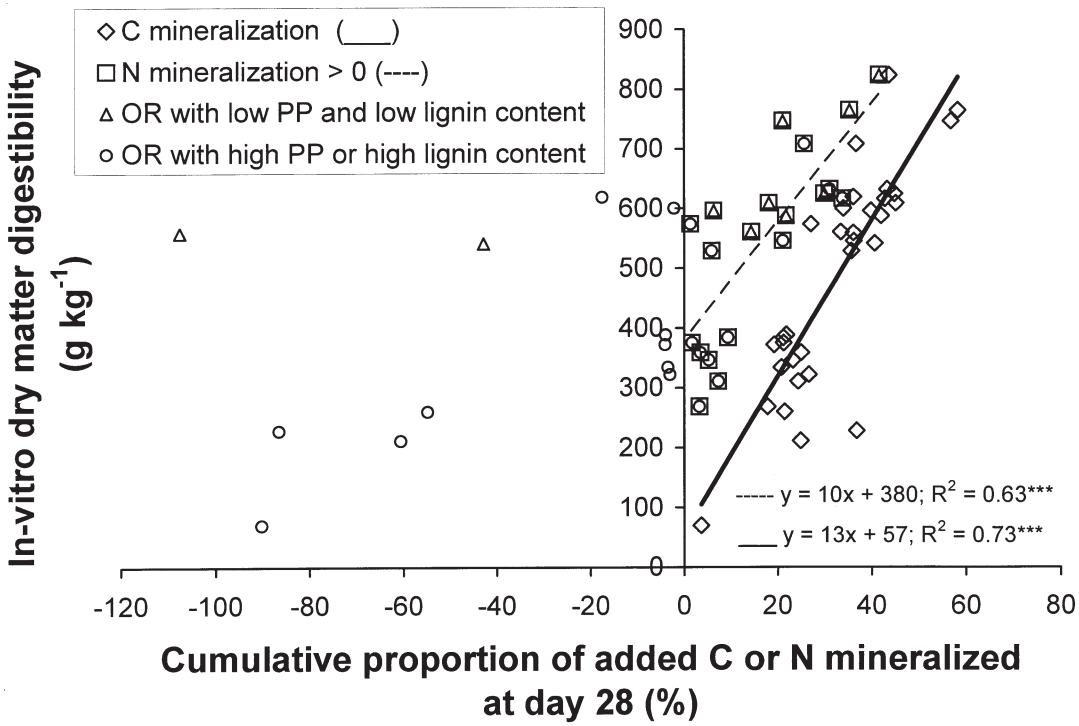

Fig. 5. Relationship between C and N mineralization as assessed using the aerobic incubation technique and the in vitro dry matter digestibility (IVDMD) assay.

lignin compared with complete composite leaves. The current inability to predict N release from *Gliricidia* residues could not be confirmed by other reported studies as mineralization of *Gliricidia* residues is usually found to be equally predictable as for other ORs used (Tian et al., 1992; Palm and Sanchez, 1991).

A relationship was observed between the soluble polyphenol content and the PBC (Fig. 1). A similar trend was also observed for the data presented by Handayanto et al. (1994) and Mafongoya et al. (1998). Research over the past 10 yr has suggested it is the tannin-like polyphenols (represented by the PBC here) that are important in regulating N availability patterns (Handayanto et al., 1994). Results from this study, however, indicate that for ORs having <80 g kg^{-1} of soluble polyphenols, the PBC was low, while for ORs with >80 g kg^{-1} of soluble polyphenols, a strong linear relationship could be observed between both quality parameters.

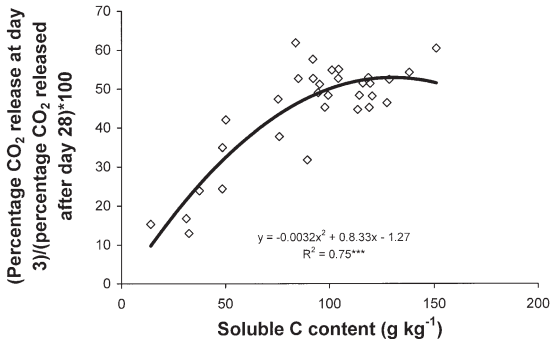

Fig. 6. Relationship between the proportions of the total amount of added residue C mineralized after 3 d over the amount released after 28 d and the soluble C content.

Considering these relationships, direct inclusion of PBC in the OR quality characterization would not improve N-mineralization–quality relationships.

Taking into account all the information presented above, the minimal dataset required to predict short-term N mineralization appears to consist of N and soluble polyphenol content. Assessment of lignin content may assist in further fine-tuning mineral N release patterns of Class A materials. Caution is needed, however, as especially measuring soluble polyphenol contents can be problematic if care is not taken to fully standardize plant material preparation and the assay itself (Constantinides and Fownes, 1994; Palm and Rowland, 1997). Especially the temperature for drying the plant materials (Dzowela et al., 1995) and the dry matter/extractant ratio affect final soluble polyphenol contents (Constantinides and Fownes, 1994). Also for measuring lignin contents, various wet chemistry approaches are possible, each with their own limitations. Also here, standardization is an important issue. Finally, increased utilization of near infrared spectroscopic approached will increase the accuracy of predictions of specific OR quality properties or even functions, thereby avoiding wet chemistry or labor-intensive incubations (Shepherd et al., 2003).

Carbon release was found to be positively related to the soluble C content of the ORs and negatively to the lignin and polyphenol content (Table 3). Lignin and polyphenol-protein complexes are known to be chemically protected from decomposition (Hammel, 1997; Giller and Cadisch, 1997). Nitrogen content of the ORs did not appear as an important factor of C release indicating that N was not limiting C release during the incubation. This is likely caused by the relatively high mineral N

Table 3. Multiple regression analysis using selected decomposition parameters as dependent variables and C, N, P, polypenol, lignin, and soluble C content as independent variables. Values in square brackets are partial correlation coefficients.

Dependent variable	Multiple regression equation	R^2
Cumulative C mineralization at Day 28 (%)	37*** − 0.092 [0.47]*** × (lignin content) − 0.184 [0.21]*** × (polyphenol content) + 0.180 [17]*** × (soluble C content)	0.86
In vitro DM digestibility (% DM)§	52*** − 1.62 [0.59]*** × (lignin content) − 1.95 [0.17]*** × (polyphenol content) + 2.88 [0.07]*** × (soluble C content)	0.83
Cumulative N mineralization at Day 28 (%)	−4.75NS‡ + 25.14 [0.76]*** × (N content) −2.76 [0.08]** × (total C content) + 1.37 [0.03]* × (lignin content) + 2.03 [0.02]† × (soluble C content)	0.88

* Significance at the 5% level, respectively.
** Significance at the 1% level, respectively.
*** Significance at the 0.1% level, respectively.
† Significance at the 10% level, respectively.
‡ Not significant.
§ Dry matter.

content of the soil at the start of the incubation (28 mg N kg^{-1} soil), which was never depleted to values below 5 mg N kg^{-1} soil for any of the treatments or incubation periods. Recous et al. (1995) observed decreases in C mineralization rates of maize (*Zea mays* L.) residues after disappearance of all soil inorganic N in treatments that initially had 10 and 30 mg N kg^{-1} soil.

For ORs showing net N immobilization (negative proportions of N mineralized) in the aerobic incubation, IVDMD values of the ORs with low lignin and polyphenol content were rather constant (about 550 g kg^{-1}) while IVDMD values of the ORs with either high polyphenol and/or high lignin content decreased with decreasing proportional N release (Fig. 5). Organic resources with low N contents and low lignin and polypenol contents usually decompose relatively slowly under aerobic conditions due to the lack of sufficient mineral N for optimal microbial activity (Recous et al., 1995). The IVDMD assay, however, is based on an anaerobic microbial decomposition phase followed by an enzyme digestion phase. In both phases, decomposition of the ORs with low biochemical resistance against decomposition is unlikely to be affected by lack of N, resulting in different assessments of decomposability when comparing IVDMD with aerobic incubation data. For ORs with either high polyphenol or lignin content, the ORs themselves have some biochemical protection against decomposition and are therefore likely not going to be easily digested during the IVDM process, even when N availability is not a limiting factor.

Various factors will impact differently on the decomposition processes as assessed under controlled laboratory conditions compared with field conditions, such as varying particle size and soil-OR contact, absence of leaching and macrofaunal influences in laboratory incubations, differences in temperature and moisture conditions, or crop root-induced influences on OR decomposition. This is illustrated for the case of maize stover and other Class III resources. While in the current study, maize stover (Sample 1) and other Class III residues were observed to result in substantial immobilization after 28 d, Vanlauwe et al. (2002b) observed that under field conditions, maize stover and ORs with similar quality actually did not substantially change maize yield or may in fact improve maize yields if they are surface applied and improve water retention in areas where water is limiting to production.

Within the context of ISFM, ORs are hypothesized to play multiple roles in improving soil fertility, besides releasing N. These are, among others, water retention and weed suppression through surface application of ORs, altering the P sorption capacity of the soil, or proton buffering and these functions may have been related to other OR quality attributes than those commonly associated with decomposition and mineralization (Cadisch and Giller, 2000). When considering the very diverse functions of ORs, the Class C residues are likely going to be

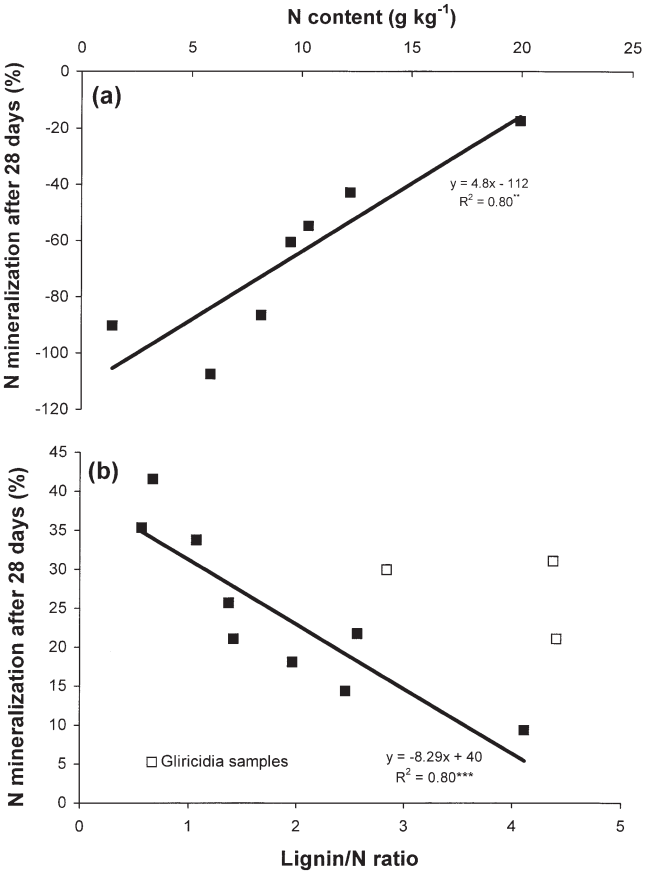

Fig. 7. Relationships between (a) the percentage of added N mineralized after 28 d and the N content of residues for treatments with N mineralization significantly below 0, and (b) the percentage of added N mineralized after 28 d and the lignin/N ratio of residues for treatments with N mineralization significantly greater than 0. In Fig. 7b, the *Gliricida* leaves (Samples 10, 11, and 29) were excluded from the regression. * and ** represent significance at the 0.1% and the 1% level, respectively.**

split further in two separate classes, one with ORs with a relatively low lignin content (Class III of Palm et al., 2001) and another class with ORs containing relatively large amounts of lignin (Class IV of Palm et al., 2001). In the longer term, the latter are likely going to decompose more slowly, as observed earlier by Vanlauwe et al. (1996), making them a good surface mulch. This would then again provide evidence for the original four-class concept of Palm et al. (2001).

CONCLUSIONS

Using a short-term aerobic incubation assay with 32 ORs with widely varying quality characteristics, three classes of ORs could be distinguished, one class showing net mineralization (Class A), a second class showing mineral N contents similar to the control soil (Class B), and a third class showing net N immobilization (Class C). Class A and B ORs both had a N content >26 g kg^{-1} but the former contained <40 g kg^{-1} soluble polyphenols with only three exceptions. Class C ORs contained <20 g kg^{-1} N. These observations confirmed the conceptual model proposed in the DSS by Palm et al. (2001), except that the latter further subdivide Class C residues in ORs with lignin content >150 and <150 g kg^{-1}. Nitrogen mineralization of Class A ORs was found to be negatively related to their lignin/N ratio while for Class C ORs, N content was explaining most of the variation in N immobilization. The minimum amount of information required to predict short-term N mineralization of ORs includes N, polyphenol, and lignin contents. It is also important to ensure that standardized approaches are used to quantify the latter two characteristics. In vitro dry matter digestibility was found to be closely related to C mineralization and to N mineralization for all ORs, except those that had a low N, polyphenol, and lignin content. Although this study focused on short-term C and N mineralization, ORs potentially fulfill many important roles for maintaining tropical soil fertility in an ISFM framework. It is important to confirm whether the OR quality concept also works for some of these other related functions.

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